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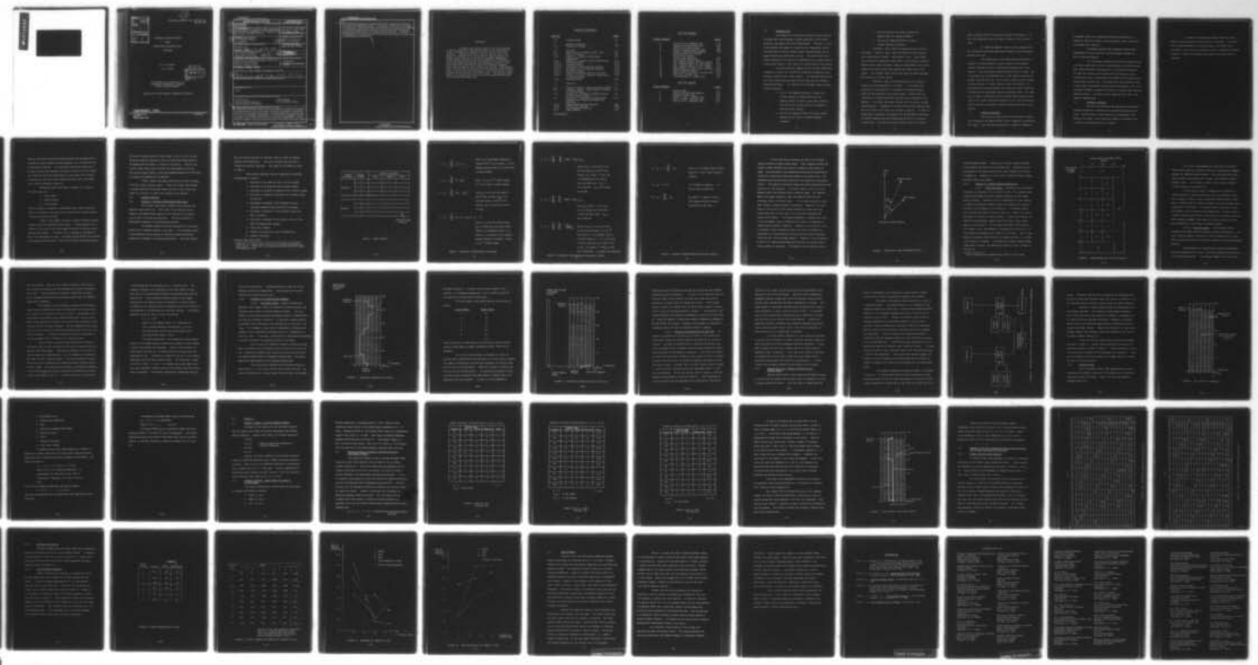

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MANNED SYSTEM DESIGN USING OPERATOR MEASURES AND CRITERIA

E. M. Connelly

N. A. Sloan

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OMNEMII, INC.

410 Pine Street, S.E.
Suite 200
Vienna, Virginia 22180

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In existing man-machine systems the human operator is typically presented a predesigned display and he must adapt his control techniques in an attempt to optimize overall system performance. Ultimate performance achieved may not rise to the designer's expectation or to the operator's capability because the design process does not account for the operator's adaptability. In this research program, ship control performance of the Officer of the Deck (OOD) → next page

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was observed and analyzed in a series of simulator experiments involving ship transit and obstacle avoidance. Three types of displays were included in the analysis. OOD control rules, and measures and criteria which describe the control technique used as well as the criteria employed in controlling the ship were derived from the individual performance data. The effect of display type on the measures and criteria which were apparently optimized by the subjects was determined.

ABSTRACT

In existing man-machine systems, the human operator is typically presented a predesigned display and he must adapt his control techniques in an attempt to optimize overall system performance. Ultimate performance achieved may not rise to the designer's expectation or to the operator's capability because the design process does not account for the operator's adaptability. In this research program, ship control performance of the Officer of the Deck (OOD) was observed and analyzed in a series of simulator experiments involving ship transit and obstacle avoidance. Three types of displays were included in the analysis. OOD control rules, and measures and criteria which describe the control technique used, as well as the criteria employed in controlling the ship, were derived from the individual performance data. The effect of display type on the measures and criteria which were apparently optimized by the subjects was determined.

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1.0 INTRODUCTION

The designer of a man-machine system typically performs his design task with knowledge of system objectives, human factors principles, and display and control requirements. However, it is the human operator who adapts his control rule (his input/output control characteristics) so that the overall system response satisfies (to the degree possible) his performance criteria. The performance that is actually achieved will be obtained in cooperation with a system that has a good system design -- and in spite of a system having a poor design.

The above argument suggests that the designer should have available as a design tool a means for estimating the operator's performance criteria and his control actions. The designer would like to know which design features support performance and which features degrade performance. The need for such knowledge suggests several research questions:

1. How can the "apparent Operator's Measure and Criteria (OMAC)" be determined? (The term "apparent OMAC" is used to mean those measures and criteria that are optimized by the operator's observed control actions.)
2. How can the "apparent OMAC" be used to predict operator control actions in specific problem situations?

3. Does the design of the system controls and displays affect the "apparent OMAC"?

4. How can the "apparent OMAC" be used to evaluate alternative displays?

Questions 1 and 2 refer to processes that are inverse to each other. Question 1 asks: given the operator's control actions, can we determine his OMAC? And Question 2 asks: given OMAC, can we predict the operator's control action in each problem situation? Optimal control theory provides a means to relate OMAC to the control actions which optimize the OMAC although the solution may not be unique. For example, there may be more than one OMAC optimized by a given set of control actions.

Question 3 refers to the determination of the effect of display and control equipment on the OMAC. To understand the significance of this problem it is necessary to distinguish between OMAC and the objectives of the control system combined with any instructions or standard operating rules that may be presented to the operator. The latter, the system objective and instructions, provide overall guidance. Examples are "direct the ship to the objective point and arrive there in one hour", and "remain in channel". In order to satisfy these instructions, the operator will develop OMAC to evaluate the system response and select appropriate actions on a moment-to-moment basis. We should note that the OMAC may or may not be

totally consistent with the instruction provided to the operator. He may make trade-offs which may lead to violations of the operation rules.

An answer to Question 4 would give the designer some way of selecting among alternative designs based on the performance expected from each.

The identification of the OMAC and the development of methods of converting OMAC to control actions in each problem situation provides a new way of representing (modeling) the human operator. There are several potential benefits of such a model. One is that OMAC may be predictable over a wide range of problems and problem situations and, thus, may be used to predict human response in those situations. A human response model using OMAC (i.e., representing the human operator by the criteria he tends to optimize) contrasts with the input/output (stimulus/response) model. This latter type of model is extensively used to represent human response but it suffers from several difficulties among which are - they are problem specific and they are generally limited to representing linear control policies.

1.1 Research Objectives

One objective of the research was to develop a design tool consisting of the apparent OMAC used by operators in performing their tasks. This required development of a method for identifying

the apparent OMAC from experimental data and development of a method for applying an OMAC to predict operator control actions and the resultant ship response.

A secondary objective was to develop a performance measurement for ship control and with this measure evaluate the effect of different displays.

The investigation reported here used data collected during a series of experiments in which a subject acting as an Officer-of-the-Deck (OOD) controlled a simulated ship in a simulated environment. His task was to direct a ship transit from the initial point to the terminal point within a pre-specified time interval while avoiding simulated contacts along the way. The experiment, using equipment known as the Surface Ship Bridge Console System (Gawitt/Beary), was run by personnel of NSRDC, Annapolis, Maryland, for purposes other than this research program. The data from that experiment was used in the research reported here.

1.2 Summary of Results

Data from the experiment was analyzed and statistically significant differences in performance using different displays were found. The differences are associated with the differences in the ability of the subject, using a particular display, to maneuver early in order to avoid passing close to a contact.

A method for computing the apparent OMAC and using OMAC to predict operator control actions was developed. The requirement was demonstrated for a purview function in the OMAC which represents a range limit of the contacts actively considered by the OOD. Evidence to support the hypothesis that display type affects OMAC is presented.

2.0 METHOD

The objectives of the research were accomplished with four analyses. Analysis I was to analyze performance data from the experiment using summary measures. Its purpose was to determine if performance is actually different with different displays and to provide results for Analysis II.

Analysis II was also a performance study but used measures that detect control actions that lead to critical conditions (near collisions). In addition, Analysis II provides the performance measure required to compare synthesized (optimal) ship responses to the subject ship responses obtained from the experiment. This comparison is required to identify apparent OMAC from a set of candidate OMAC.

Analysis III was an initial test of OMAC where optimal ship responses were developed in a one-contact problem. The purpose of the analysis is to establish a set of factors to be included in OMAC for test in Analysis IV.

Once a set of OMAC factors were established, the apparent OMAC was determined in Analysis IV. Composite performance data representing performance of subjects working with a particular display are compared to performance data from the set of OMAC. From that comparison, the OMAC apparently used by the operators with each type of display are identified.

2.1 Description of the Manual Control Task

The subject acting as an Officer of the Deck (OOD) commands the ship course and speed required to transit the simulated ship from the initial position to the final position while avoiding each simulated contact (other ship) encountered. The distance between the initial and final positions is approximately 30 miles and the time allotted for the transit is 90 minutes.

The subject sits in front of a simulator console which has three computer driven CRT displays and a number of control switches. The CRT display directly in front of the subject is the main display and provides visual information about the location of (own) ship and contacts. The configuration of that display varies with the particular display function simulated, and thus, is an experimental variable. The CRT display on the subject's left provides a list of contact information such as location, speed, heading, and closest point of approach (CPA). This display is termed "LIST". The display on the subject's right provides data on ship course and speed. It can also provide data on "trial" course and speed which the subject may input for evaluating decision command changes. There are a number of control switches which allow the subject to select display functions, to input trial course and speed, and to direct course and speed change commands to an individual representing the Helmsman.

The task of the subject OOD's is to visualize or calculate the possible courses from present ship position to the objective point.

Then, by taking into account the contact positions and velocities and by utilizing the various display functions available, he is to direct the ship to the objective position. The instructions read to the subject prior to each trial are "the objectives during the run are to be at the rendezvous at the end of the 90 minute period, to pass clear of all contacts (if possible by more than 4,000 yards), to obey the Rules of the Road, and to observe economy of operation".

Performance with three types of displays is of interest. The three types are:

1. "OLD system"
2. "PACS system"
3. "RVV system"

The OLD system is essentially a conventional radar display where the center of the screen is the position of own ship and the relative position of contacts are shown as blips.

PACS, a new display, provides a number of different display functions which are selectable by the subject. PACS (probable area of collision) is the name of the function <u>and</u> the name of the display system providing that function. In PACS, LIST is available on the left-hand CRT. Also, the subject can select a new display function PACS or true velocity vector modes on the center CRT. With the PACS mode, the display provides

the locus of collision points for each contact for all own ship courses. Since this requires projection of future own ship and contact positions, the display aids the subject in selecting a new course. With the true velocity vector mode, velocity vectors are superimposed on the own ship and the contact "blips" to show the predicted position of all the ships at a future time selected by the operator.

Finally, another new display termed "RVV system" includes LIST plus relative velocity vectors. These are vectors superimposed on contact blips that indicate the relative position of each contact with respect to own ship at a future time selected by the operator.

2.2 Method of Analysis

2.2.1 Analysis I: Summary Performance Measurement

Ten summary performance measures were developed and applied to each subject run. Since some of the measures may be related, a correlation/factor analysis of all measures for all subject runs (a total of 40 runs) was performed. This led to selection of performance measures for the performance analysis.

The selected measures were then analyzed with a two factor ANOVA with a repeated measure on one factor. This permitted control of the differences among subjects as individual subject performance measures are related to his average performance. Only eight subjects

(four for head-up[1] and four for north-up[1]) have run under all display systems (OLD-PACS-RVV). Thus not all subject data are used to evaluate the summary measures. The model for the ANOVA is given in Table 1.

The summary measures used are listed below and defined mathematically in Table 2.

1. Summation of the absolute value of course changes.
2. Summation of the absolute value of speed changes.
3. Summation of samples* of difference from reference speed.
4. Summation of samples* of deviation from straight course to objective.
5. Summation of samples* of CPA (Closest Point of Approach) violations where own ship is privileged.
6. Summation of samples* of CPA violations where own ship is burdened.
7. Summation of samples* of the inverse of time to CPA given a projected CPA violation.
8. Total travel distance.
9. Distance from objective at end of allotted time.
10. Number of decisions.

*Samples taken each minute

1 "Head-up" is a display mode where the top of display corresponds to ship's course. "North-up" is a display mode where the top of display corresponds to north.

Display Orientation	Subject Number	DISPLAY SYSTEM		
		OLD	PACS	RVV
North-up	1			
	2			
	3			
	4			
Head-up	6			
	7			
	8			
	9			

Scores for each maneuver

TABLE 1 ANOVA MODEL

1. $F_1 = \sum_{i=1}^{N_1} \left| \Delta\psi_i \right|$, where $\Delta\psi_i$ is the number of degrees of change of the i^{th} course change, $|\;|$ is the absolute value operation, N_1 is the number of course changes

2. $F_2 = \sum_{i=1}^{N_2} \left| \Delta S_i \right|$, where ΔS_i is the i^{th} speed change, N_2 is the number of speed changes.

3. $F_3 = \sum_{k=1}^{N_3} \left| S_k - S_{Rk} \right|$, where S_k is the own ship speed on the k^{th} time interval, S_{Rk} is the reference speed on the k^{th} time interval, N_3 is the number of time intervals.

4. $F_4 = \sum_{i=1}^{N_1} \sin \left| \psi_i - \psi_{Ri} \right| \cdot S_i \cdot \Delta T$,

where ψ_i is own ship actual course, ψ_{Ri} is course from own ship present position to the objective point, S_i is speed, ΔT is duration of time interval between samples of process, i refers to the i^{th} course change.

TABLE 2 SUMMARY PERFORMANCE MEASURE

5. $F_5 = \sum_{k=1}^{N_3} \sum_{i=1}^{N_4} (4000 - CPA_{ki}) M_{ki}$,

where CPA_{ki} is the CPA of own ship and contact i on the k^{th} time interval M_{ki} equals 1 if own ship is privileged and if the CPA is less than 4000 yards. M_{ki} is zero otherwise. N_4 is the number of contacts.

6. $F_6 = \sum_{k=1}^{N_3} \sum_{i=1}^{N_4} (4000 - CPA_{ki}) N_{ki}$,

where N_{ki} equals 1 is own ship is not privileged and if the CPA is less than 4000 yards. N_{ki} is zero otherwise.

7. $F_7' = \sum_{k=1}^{N_3} \sum_{i=1}^{N_4} \frac{P_{ki}}{TCPA_{ki}}$, where $TCPA_{ki}$ is the time to CPA of own ship and contact i on the k^{th} time interval. The smallest value of TCPA permitted is 1, i.e., if the time to CPA is less than one, TCPA is set to one. P_{ki} equals 1 if CPA_{ki} is less than 4,000 yards. P_{ki} equals zero otherwise.

TABLE 2 SUMMARY PERFORMANCE MEASURE (CONTD)

8. $F_8 = K \sum_{k=1}^{N_3} S_k$, where K is a constant which converts speed over a one minute interval to distance.

9. $F_8 = D\,(T)$, D is distance to objective. T is time at end of experiment.

10. $F_9 = \sum_{k=1}^{N_3} B_k$, B_k equals 1 if speed or course has changed during the interval; B_k equals zero otherwise.

TABLE 2 SUMMARY PERFORMANCE MEASURE (CONTD)

The first and second measures are sums of the absolute values of course and speed change values. These measures combine the number of OOD commands with amount of change in ship course and speed. The third measure is the displacement (at the end of the interval) of the ship from a path from present ship position to the objective point. The reference course and ship course required for the measure are illustrated in Figure 1. The measure is intended to measure the amount of deviation from the straight line to the objective. The fourth measure is the sum of the absolute value of the deviation from a reference speed. The reference speed is the speed required to reach the objective within the time remaining, times a correction factor. The correction accounts for the delay caused by contact avoidance maneuvering. Measure 5 is a summation of the amount of CPA violation (distance to contact less than 4,000 yards) where the own ship is in a privileged orientation with respect to the contact. A privileged orientation as defined by the rules of the road (Zadig, 1972), provides that the contact is responsible for making contact avoidance maneuvers. Measure 6 is the same as 5 but is computed in those situations for which own ship is burdened (i.e., responsible for contact avoidance maneuvering) and all other situations that do not fall in the privileged category. Measure 7 is the reciprocal of time to the closest-point-of-approach (CPA) for all contacts where a contact violation is projected. The measure value increases as time-

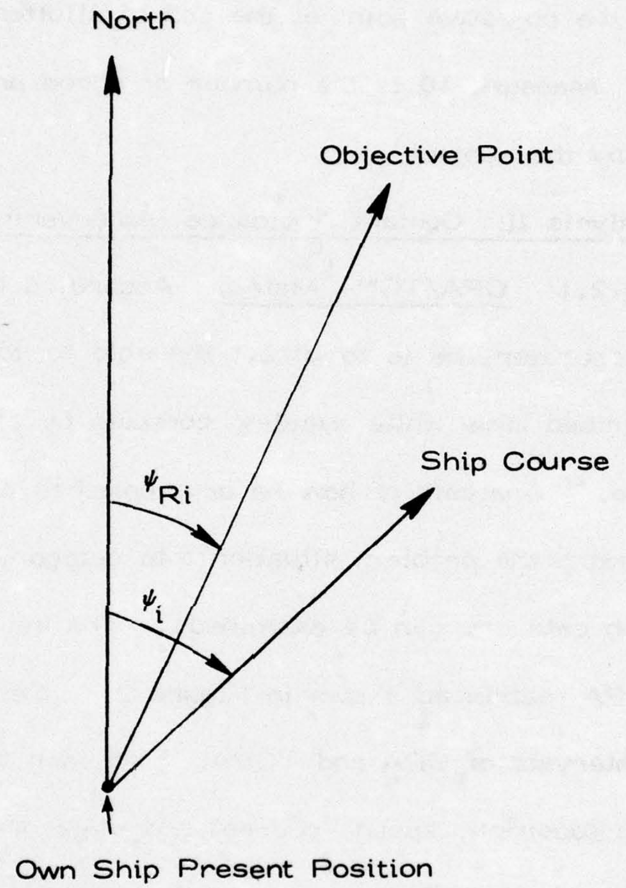

FIGURE 1 DEVIATION FROM REFERENCE PATH

to-CPA becomes smaller. Measure 8 is the total distance travelled by the subject from start to end of allotted time. Distance from own ship position to the objective point at the end of allotted time is given by Measure 9. Measure 10 is the number of speed and course change decisions made by the subject.

2.2.2 Analysis II: Contact Avoidance Maneuvering

2.2.2.1 CPA/TCPA[1] Matrix According to the instructions provided to the operator, he is to direct the ship to the objective point within the prescribed time while avoiding contacts by at least 4,000 yards if possible. Analysis of how he accomplishes the task requires a method of dividing the problem situation into categories so that performance in each category can be examined. The selected method uses a CPA/TCPA matrix as shown in Figure 2. Cells in the matrix correspond to intervals of CPA and TCPA. At each time interval, the state of the ship (position, speed, course) and state of each contact specify a cell condition. For N contacts there are N cell conditions. For example, Cell 1 corresponds to a projected CPA of from 0 to 1.5 miles which is projected to occur within 0 to 5 minutes. Cell 21 represents the situation where the CPA has already occurred, i.e., range to the contact is increasing. Projected CPA violations (passing within 4,000 yards (2 miles)) are identified by entries in Cells 1 through 12 and Cell 19.

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[1] CPA is closest point of approach and TCPA is time to CPA.

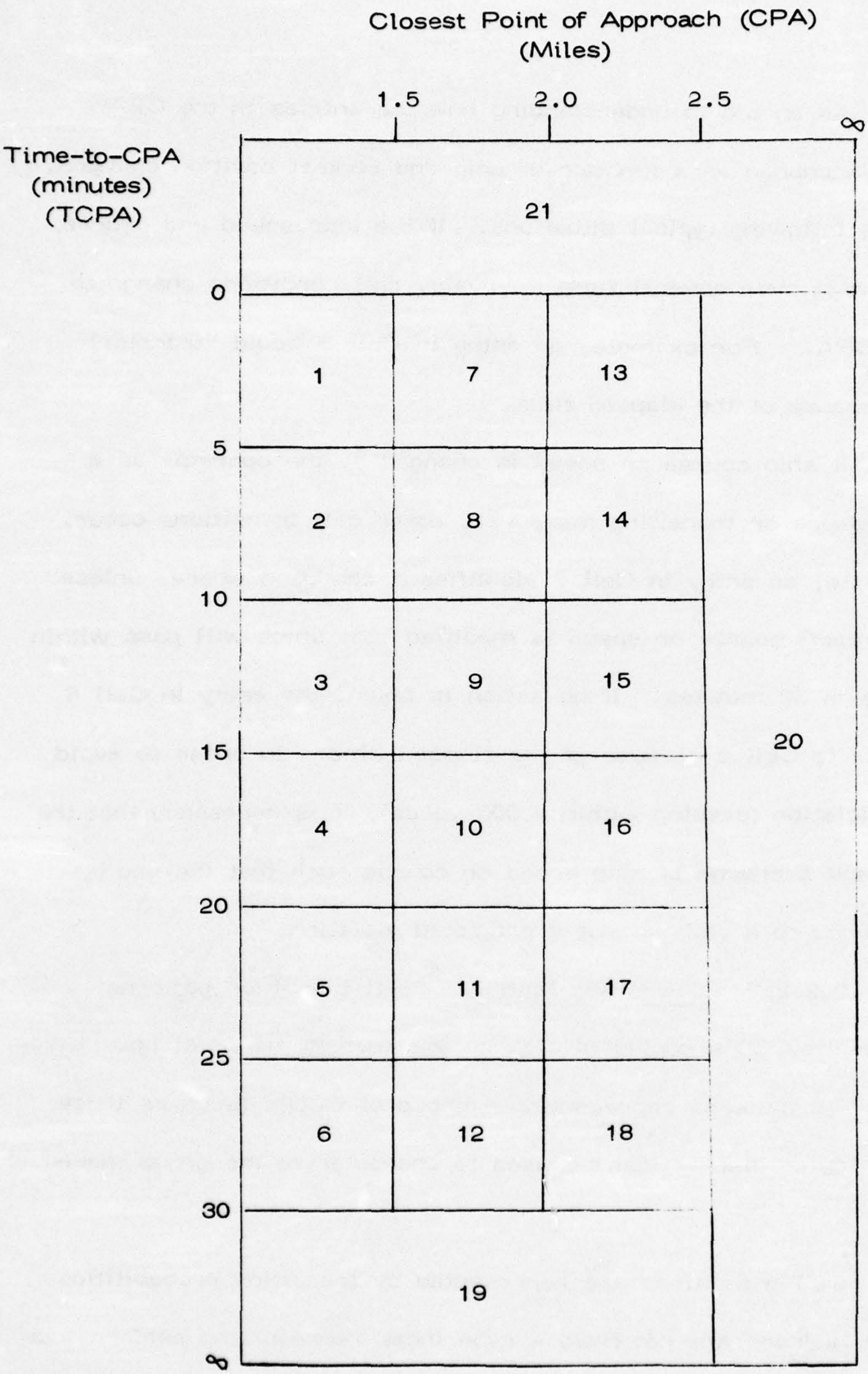

FIGURE 2 DEFINITIONS OF CPA/TCPA CELLS

As an aid to understanding how the entries in the CPA/ TCPA matrix change as a function of ship and contact position changes, consider the following typical situations. If the ship speed and course remain constant over several time intervals, cell conditions change to decrease TCPA. For example, an entry in Cell 6 would "transfer" to Cell 5 because of the elapsed time.

If ship course or speed is changed by the operator as a contact avoidance or transiting maneuver, other cell transitions occur. As an example, an entry in Cell 6 identifies a condition where, unless ship (or contact) course or speed is modified, the ships will pass within 4,000 yards in 30 minutes. If no action is taken, the entry in Cell 6 will transfer to Cell 5 because of the elapsed time. In order to avoid a contact violation (passing within 4,000 yards), it is necessary that the OOD command a change of ship speed or course such that the entries are transferred to a cell without a projected violation.

2.2.2.2 Transition Matrix Cell transition patterns characterize the OOD's contact avoidance and transit maneuvering. Likewise, transition patterns representing a group of OOD's (such as those using a particular display) can be used to characterize the group maneuver patterns.

Cell transitions are represented by transition probabilities since cell sequences are not fixed - even those representing performance of an individual performer. The transition pattern from a given cell,

say Cell i, is recorded in the associated row of a 21 by 21 transition matrix. Probability $\left(P_{ij}\right)$ is the probability of transferring to Cell j from Cell i on each time interval. In the experiment, data was sampled every minute so that the probabilities are associated with the indicated transfer in each one minute interval. Entries in the diagonal elements of the matrix, where i equals j, have a special meaning. Probability values P_{ii} are related to the mean number of intervals for which an entry in Cell i will remain in Cell i. P_{ii} is computed according to the formula:

$$P_{ii} = \frac{I - 1}{I},$$

where I is the mean number of intervals an entry is in Cell $_{ii}$ before transition to another cell. Calculation of the probabilities off the diagonal from the experiment data uses the formula:

$$P_{ij} = \frac{N_{ij}}{M_i} (1 - P_{ii}), \; i \neq j$$

where N_{ij} is the number of transitions from Cell i to Cell j and M_i is the total number of transitions from Cell i. The term $(1 - P_{ii})$ is the probability that a transfer to another cell will occur in each time interval.

Although the above description of the CPA/TCPA matrix, the transition matrix, and the method of calculating transition probabilities is presented as though cell entry changes occur for only one contract at a time, there are in fact multiple simultaneous changes.

Each course or speed change commanded by the OOD can cause multiple simultaneous changes in the cell entries. Transition probabilities are developed from transition events that occur both simultaneously and throughout the experiment. When a transition matrix is developed to represent performance of a group of subjects, data used is obtained from all subject runs. In spite of the fact that the transition matrix probabilities represent both simultaneous and sequential occurrences and multiple subject runs, it is often convenient to visualize the transition matrix as describing the relationship between own ship and one contact - in the presence of many other contacts. Thus, it is possible to trace a likely path of cells from the point of contact activation until the ship reaches the objective point. Different contact initial conditions (conditions at time of contact activation) may lead to different cell sequences.

2.2.2.3 Comparison of Ship Response Patterns

Considerable analysis of ship maneuvering patterns can be accomplished by inspection of the transition matrix probabilities. For example, an entry in Cell 6 corresponds to a projected CPA violation in 25 - 30 minutes. Transitions to Cells 5, 4, 3, 2, 1 will occur if no OOD control actions exist to cause a transfer to cells where CPA violations

are not projected. Also, as time to CPA decreases in cells where a CPA violation is projected, the less desirable the situation represented by the cell. Thus examination of transition probabilities provides a way of evaluating performance and comparing performance with different experimental treatments.

One difficulty in the quantitative evaluation of performance, using transition probabilities alone, is that transition from a given cell is not weighted by the probability the cell is "used". For example, with one treatment (one display type), transition from Cell 3 may not be as good (a high probability of transfer to a cell that does not project a CPA violation) as that of another treatment. But the probability that an entry will be in Cell 3 may be so small that transitions from Cell 3 may be of little consequence. A method for solving this problem is described in the next paragraph after introduction of a required concept.

Once a contact is passed, where distance from contact is increasing, there is little likelihood that the ship will maneuver so as to approach that contact again. Assuming that condition is true, Cell 21 can be treated as an absorbing cell, i.e., the probability of leaving the cell after the cell is entered is zero. With that assumption, the transition matrix can be analyzed as an absorbing Markov Process (Kemeny & Snell, 1960). This means that the process is considered as starting in any cell (but especially Cells 19 and 20) and transferring to a series of other cells ending in Cell 21. An entry may return to a given cell

in that process but once entering Cell 21, it remains there. The analysis of interest is the calculation of the mean number of times each cell will be entered before entering the absorbing state given the starting cell. This provides the desired measure of cell usage. Calculation of the measure required formulation of a matrix Q which is identical to the transition matrix P except that row 21 and Column 21 (corresponding to the absorbing cell) have been removed. The desired measure is given by matrix R (a 20 X 20 matrix):

$$R = (I - Q)^{-1}$$

where I is the identity matrix, "-1" represents the matrix inverse operation, and elements r_{ij} of R are the mean number of times the process enters Cell j given the process starts in Cell i.

The next and final step in the comparison of ship response patterns is to compare subject controlled ship response for each display to each of the optimal ship responses. MT(I) is used to denote the mean number of times Cell I is entered before the process enters the absorbing cell (21). Comparison is made with the sum of the squared differences of the cell mean entries (MT(I)). The comparison is made of the MT in Cells 1 - 5 and 7 - 11, deemed the critical region cells since they represent a situation where a CPA violation (less than 2 mile CPA) is projected. The Wilcoxon matched-pair signed-ranks test was

used for the comparison. Subjects performing in each set of two displays provided the matched pairs. Performances with the three displays were compared two at a time.

2.2.3 Synthesis of the Optimal Ship Response

2.2.3.1 Coordinate System Dynamic programming (Bellman, 1962, Elgerd, 1967) is a method for computing optimal ship responses which utilizes a discrete analysis technique. The area between the ship starting position and objective position is approximated by a grid as illustrated in Figure 3. A ship path is approximated by the straight lines connecting the grid intersections as illustrated in the figure. For example, a ship's path is represented by identifying the sequence of grid intersections (identified as the X,Y coordinates) as a function of time. In this way, a smooth path is represented approximately by a path of straight line segments as shown in the figure.

With this grid, the problem of finding a continuous optimal path is converted to one of finding the locus of points on the grid that, when connected by straight lines, provide the optimum grid path from the starting position (SP) to the objective position (OP). This path is taken as an approximation to the continuous optimal path.

The grid structure selected has 45 increments along the basic course, i.e., the x axes, the line from the SP to the OP. Six levels of deviation from the base course, three per side, are provided

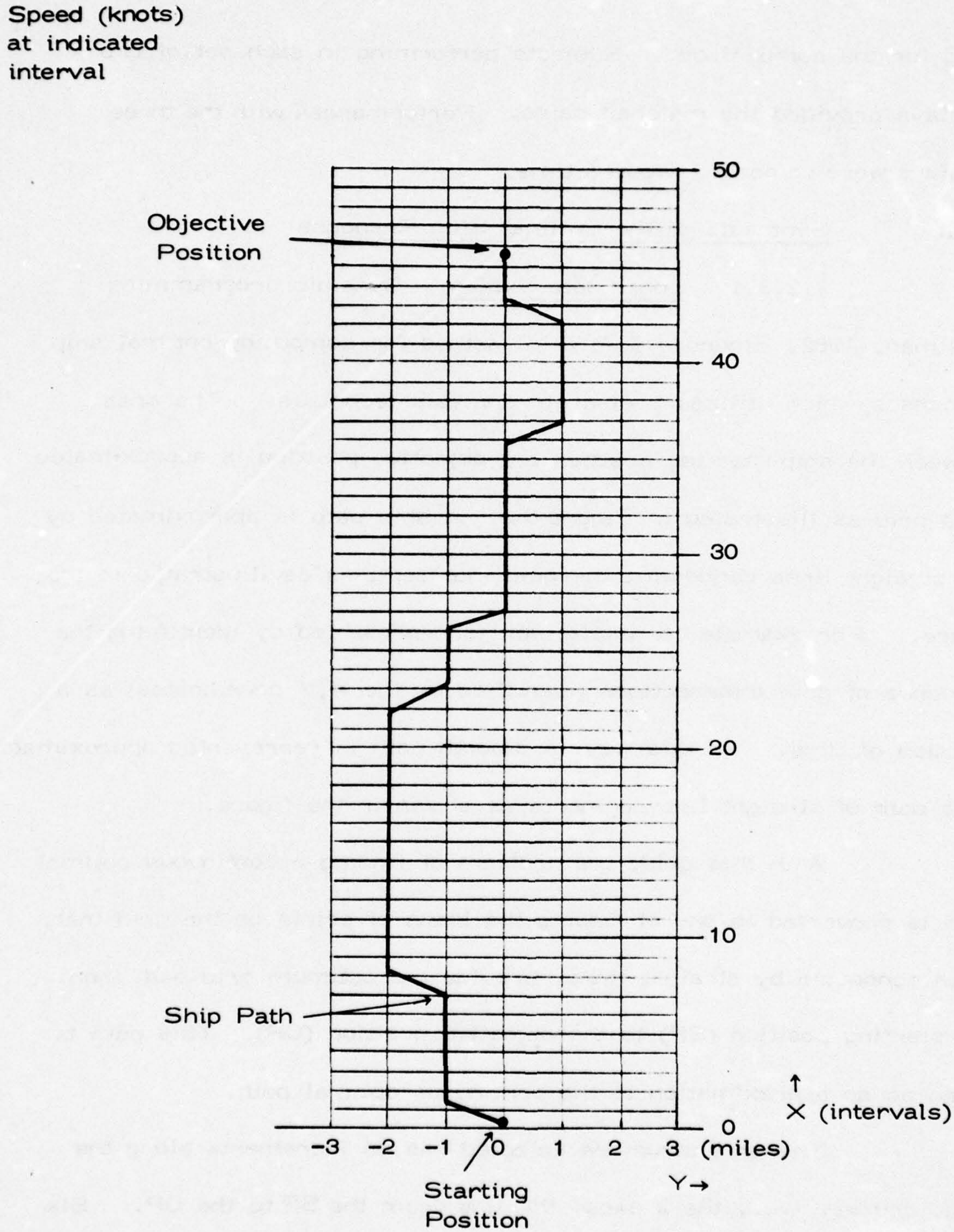

FIGURE 3 PROBLEM COORDINATE SYSTEM

as shown in Figure 3. Scaling of one mile per interval in the Y direction (Y is measured perpendicular to the X direction) allows for a deviation of $\pm$ 3 miles from the base course.

The ship's speed is also approximated by seven levels as follows:

Level Number	Speed (knots)
1	10
2	12
3	16
4	18
5	20
6	22
7	25

Contact positions are superimposed on the grid as a continuous factor of time so that range to contact, projections of CPA, TCPA can be computed.

As an aid to understanding the calculation by which the optimum path is determined (to be described in the next section), consider the problem of specifying a ship path (not necessarily the optimum path) from the start to the destination. Referring to Figure 4, consider that the ship is at the starting position. By examining the position, course and speed of each observable (activated) contact, a feasible path to the destination must be envisioned. The path is to be designated by

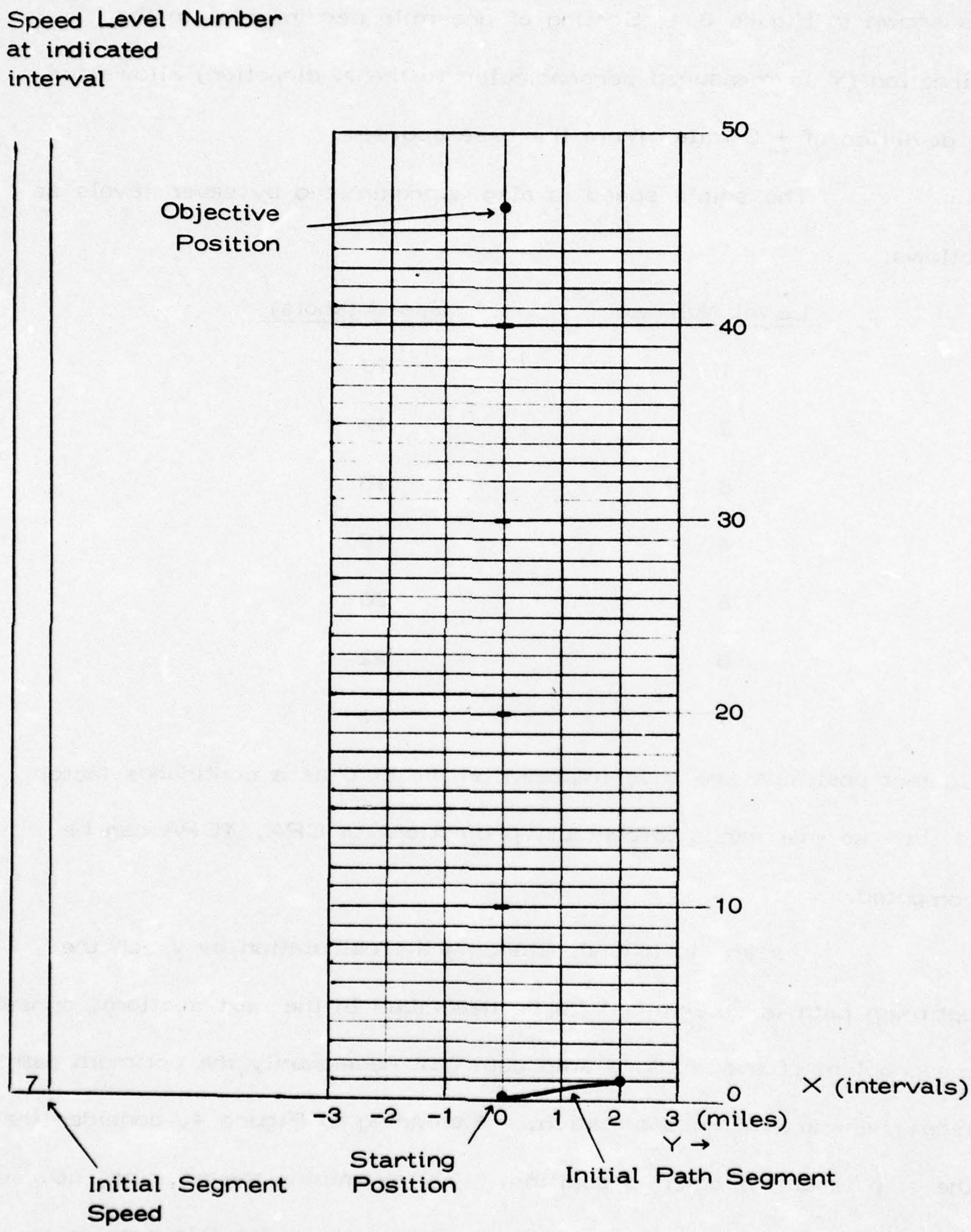

FIGURE 4 METHOD OF CONSTRUCTING SHIP PATH

specifying the grid intersections and ship speed along each path segment connecting the grid intersections. The path is to be selected so that the minimum range to each contact is not less than 4,000 yards and the destination is reached within the allowed 90 minutes. The first path interval consists of a segment from the initial position where X equals 0, to one of the grid intersections where X equals 1. The particular intersection selected at that interval is identified by a value of Y (in this case 2). Along that segment, a speed level number is selected as indicated in the left portion of the figure. Obviously, this procedure is repeated for increasing values of X until the objective position is reached.

2.2.3.2 Method of Calculating Optimum Ship Path The problem of specifying the optimum path is similar to the process described above except that the path selected must optimize the criteria of interest. Two types of problems exist in specifying the optimum path. One is the large number of possible path and speed combinations prevent direct evaluation of each possible combination. Even though the number of levels of deviation from the base line (the values of Y) and the number of speed levels are small, the number of possible combinations of paths and speed is large. Consider that on the first interval, where X equals 1, there are seven Y deviation levels and seven speed levels - a total of 49 combinations. At the next interval, where X equals 3, there are another 49 combinations of Y deviation and speed. Each combination of the first interval could be associated with a combination of the second

interval to form a path, and thus there are 49 times 49 possible combinations for the first two intervals. Extension of this reasoning for subsequent intervals reveals that for the 45 intervals, there are 49 to the 45th power possible path and speed combinations to consider. This large number of combinations prevents direct calculation of the value of each combination in order to determine which is best. This problem can be solved using dynamic programming which capitalizes on the fact that each portion of an optimal path is also optimal. Dynamic programming provides a systematic way to develop candidate optimal paths step by step along each interval in the X axis until the destination is reached where the true optimal path is identified.

The other problem referred to is that contacts are activated at various times throughout the problem with some activated initially and others activated as the ship progresses toward the destination. A path that is optimal with one set of contacts may not be optimal when an additional contact is observed. Thus, when a new contact is activated, the present position of the ship is noted and a new optimal path is determined using present ship position as a starting point. The calculation then proceeds as before but now includes the new contact.

2.2.4 Analysis III and IV: Method of Determining the Apparent OMAC

Optimal control theory is the connecting link between criteria to be optimized and optimal control actions (which are applied to the ship to produce optimal ship paths). Given the criteria, control objectives

(transit to destination), and limitations on control actions, optimal control theory is used to synthesize the optimal control actions.

Calculation of the optimal control actions from criteria is a synthesis process. The inverse process, i.e., calculation of the apparent criteria (the criteria which is optimized by the observed control actions), is not a synthesis process since there is no formal way of solving for such criteria. However, the problem can be solved by repeated application of the synthesis procedure in which a set of candidate criteria is selected and using each criteria, the associated optimal control actions and therefore associated optimal ship response, are synthesized. The set of optimal ship responses generated is compared to the ship responses observed in each performance grouping of the experimental data. A performance group represents the set of experimental data for all subjects using a particular display. The mean number of entries in each CPA/TCPA matrix cell, described previously, is used for the comparison. That optimal ship response judged to be closest to the ship response of each performance group identifies, by deductive reasoning, the criteria to be associated with the performance group.

This method of identifying the apparent OMAC is illustrated in Figure 5. It must be noted that the criteria associated with each performance group is only the most representative of the set of criteria initially selected and it should also be noted that the criteria may not be

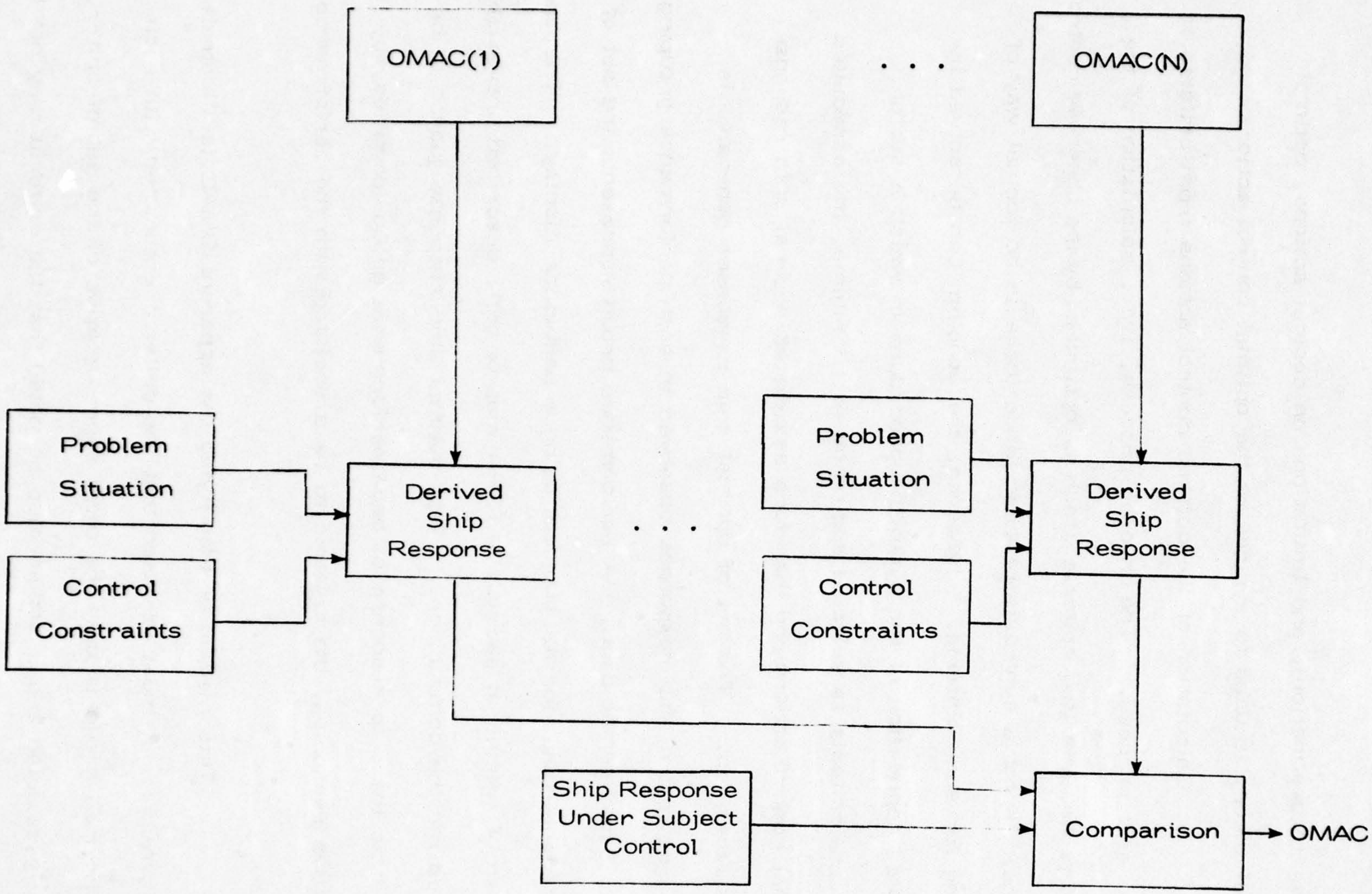

FIGURE 5 METHOD OF IDENTIFYING THE APPARENT CRITERIA USED BY AN OPERATOR

unique. Criteria so identified can be considered as representative of the actual criteria (and therefore useful) only when it is predictive, i.e., can accurately predict operator's control actions in problem situations.

Synthesis of optimal control actions was accomplished with two problem situations. One employed a single contact crossing in front of own ship and the other used all 25 contacts in accordance with the experiment design described previously. Evaluation of candidate OMAC functions and parameter values was first accomplished with the simpler one-contact problem. Based on the results of the one-contact problem (Analysis III), candidate OMAC were selected for test with the 25-contact problem (Analysis IV).

Contact and own ship positions for the one-contact problem are shown in Figure 6. Contact initial positions and courses for the 25-contact problem are shown in Figure 7. Table 3 provides the times of activation (time contacts are first presented to the operator). These are the contacts that must be avoided by the subject OOD as he directs the ship to the objective point.

2.2.5 Candidate OMAC

A set of candidate OMAC's were developed based on the instructions and operation rules given to the subject, and the Maritime International Rules of the Road. Factors that could be included in candidate OMAC are:

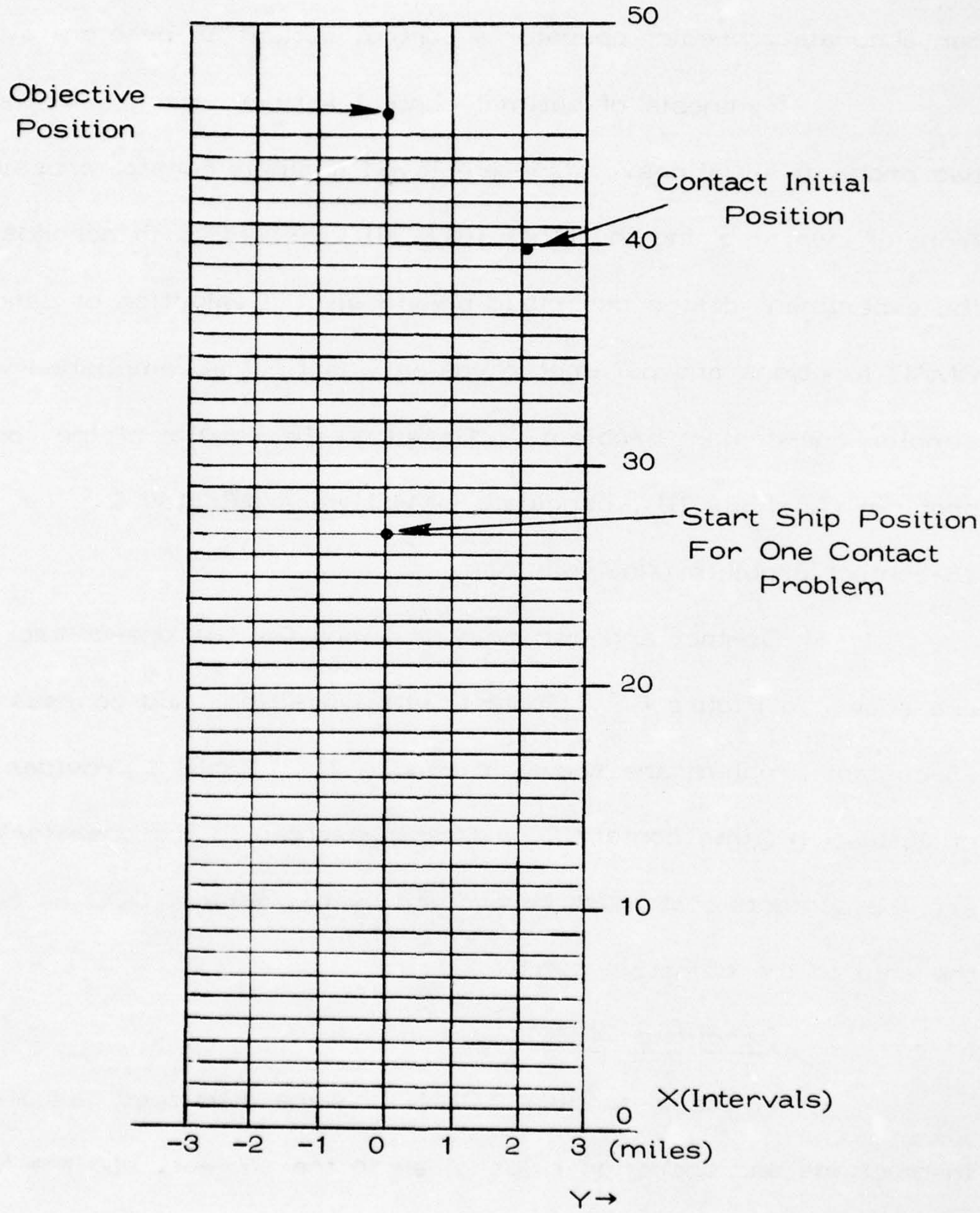

FIGURE 6 ONE-CONTACT PROBLEM

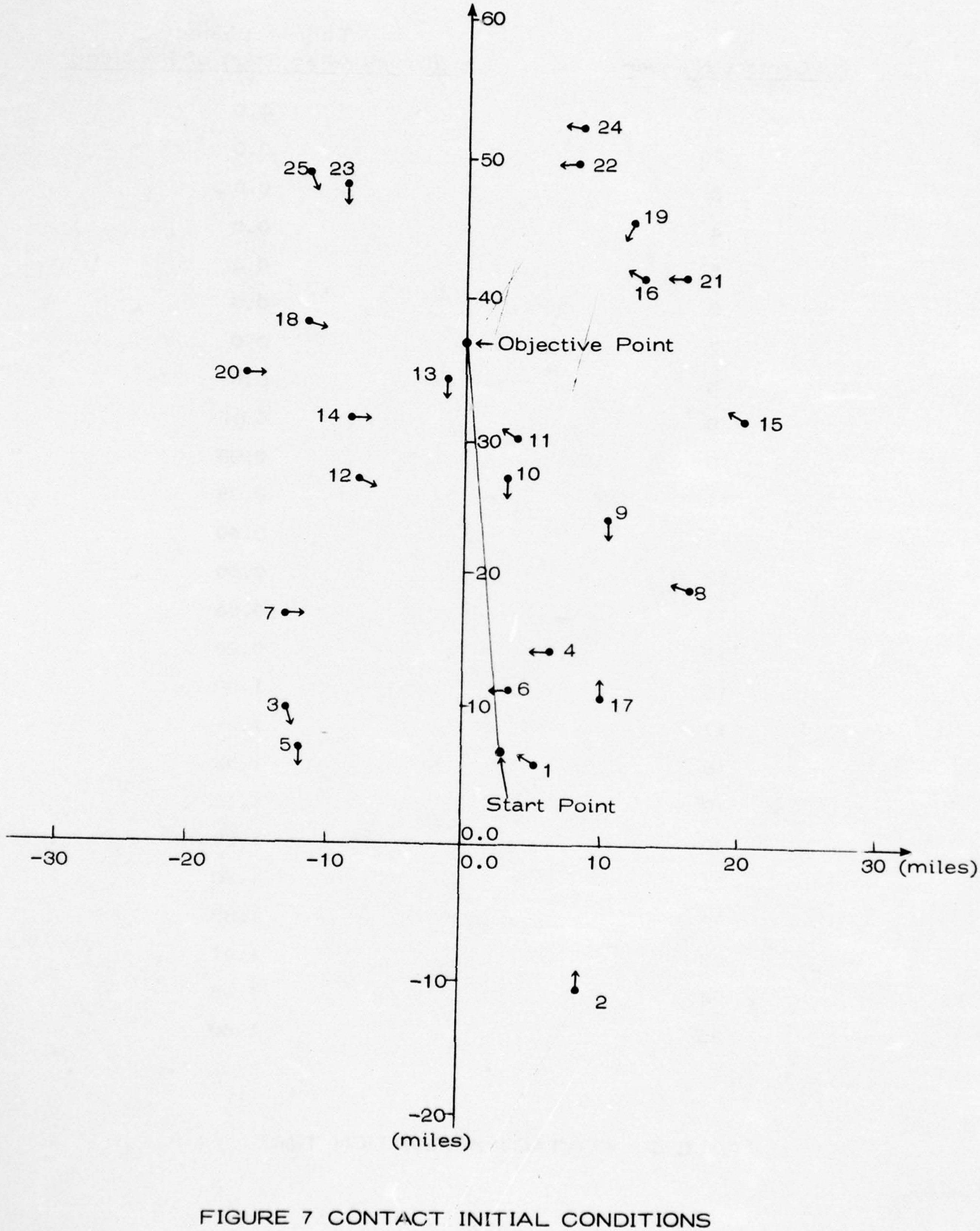

FIGURE 7 CONTACT INITIAL CONDITIONS

Contact Number	Time Activated (Hours After Start of Problem)
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	0.0
8	0.0
9	0.01
10	0.08
11	0.35
12	0.40
13	0.50
14	0.55
15	0.90
16	1.00
17	1.01
18	1.08
19	1.18
20	1.20
21	1.26
22	1.35
23	1.41
24	1.46
25	1.50

TABLE 3 CONTACT ACTIVATION TIME

1. Accumulated time

2. Distance from destination

3. CPA

4. Economy of operation (fuel usage)

5. Rules of the road

6. TCPA

7. Number of decisions

8. Total travel distance

The approach used was to select factors for an OMAC, to determine the OMAC coefficients which best predict experiment performance data and to evaluate the predictive capability of that OMAC. One function selected is:

$$C_1 = A \times T + B \times CPA + C \times {}^1/TCPA$$

where A, B, C are weighting coefficients, T is accumulated time since start of run, CPA is closest point of approach, and TCPA is time to CPA.

A limit in the weighting coefficients was used as follows:

$$A + B + C = 1, \quad A, B, C \geq 0,$$

thus only two weightings can be selected freely and those must be less than unity.

An alternate and simpler OMAC function was formed as:

$$C_2 = A \times T + \times CPA/TCPA$$

where $A + B = 1, \qquad A, B \geq 0$

The second OMAC (C_2) is a two-factor system which was eventually selected to simplify the initial investigations. Both OMAC constructions ignore some factors listed above which may be important. However, it was also important to simplify the problem for the "first cut".

3.0 RESULTS

3.1 Analysis I Results: Summary Measure Results

Correlation of the values of the ten summary measures over all subject runs reveals that strong relationships exist between several measures. Measure pairs found to be strongly related are:

1 ⟷ 10

3 ⟷ 8 (Refer to page 2-5 for description of summary measures)

4 ⟷ 9

6 ⟷ 7

Analysis of Variance (ANOVA) on the summary measures showed no significant differences due to display orientation (head-up or north-up). Also, there are no significant differences in performance due to display type at the $\alpha = 0.05$ level. There is significance of performance due to display type with measures 7 and 8 (the inverse of time-to-CPA and total travel) at the $\alpha = 0.1$ level.

3.2 Analysis II Results: Mean Number of Entries in Critical Region

The Wilcoxon matched-pairs signed-ranks test was applied to compare performance as follows:

1. PACS vs. RVV
2. PACS vs. OLD
3. OLD vs. RVV

Results showed that in comparing PACS vs. RVV, PACS provided significantly fewer entries in the critical region (significant at $\alpha = .01$ level). Comparing PACS vs. OLD showed PACS superior but significantly superior only at the $\alpha = .10$ level. There was no significant difference between performance with OLD and RVV. Data analysis Tables 4, 5 and 6 provide the test results. Note that in the PACS vs. OLD analysis, only one subject out of the eleven subjects performed better with OLD.

3.3 Analysis III Results: Synthesis of Optimal Controls for One-Contact Problem

The purpose of Analysis III was to evaluate candidate OMAC functions so that a final selection could be made for the 25 contact problem (Analysis IV). While this purpose was accomplished, and the results are provided at the end of this section, the need to include a purview constraint in the optimization process was discovered. This is an important result because it shows that modeling of subject performance cannot be accomplished without establishing a purview limit. With the purview limit, the synthesis considers all contacts within purview (range) but ignores all others. However, the purview limit introduces an additional parameter (range of purview). For this reason, the set of candidate OMAC was revised to include the purview constraint as a parameter and to use the simpler OMAC function presented previously and repeated here:

$$C_2 = A \times T + B \times CPA/TCPA \text{ (for all contacts within purview)}$$

Number of Entries in Critical Cells (1, 2, 3, 7, 8, 9)

Subjects	Display Type RVV	PACS	Difference	Rank
A5	6	1	5	+
A8	5	2	3	+
A10	17	3	14	+
A12	3	0	3	+
A14	13	6	7	+
B4	6	0	6	+
B6	13	8	5	+
B7	3	3	0	
B10	7	1	6	+
B14	3	2	1	+

$N = 9$ $T = 0$

$C_{.01} = 2$ (two tailed)

TABLE 4 PACS vs. RVV
Wilcoxon Test

Number of Entries in Critical Cells (1, 2, 3, 7, 8, 9)

Subjects	Display Type OLD	PACS	Difference	Rank
A4	5	3	2	3.0+
A6	5	10	-5	8.5-
A8	3	2	1	1.5+
A10	12	3	9	10.0+
A12	4	0	4	6.0+
A14	10	6	4	6.0+
B4	3	0	3	4.0+
B6	8	8	0	
B7	4	3	1	1.5+
B10	6	1	5	8.5+
B14	6	2	4	6.0+

N = 10 T = 8.5

$C_{.05}$ = 8 (two tailed)

$C_{.10}$ = 11 (two tailed)

TABLE 5 OLD vs. PACS
Wilcoxon Test

Number of Entries in Critical Cells (1, 2, 3, 7, 8, 9)

Subjects	Display Type OLD	RVV	Difference	Rank
A7	11	0	11	12+
A8	3	5	-2	4-
A10	12	17	-5	10-
A12	4	3	1	2+
A14	10	13	-3	6.5-
B4	3	6	-3	6.5-
B6	8	13	-5	10-
B7	4	3	1	2+
B8	9	6	3	6.5+
B10	6	7	-1	2-
B12	0	5	-5	10-
B14	6	3	3	6.5+

$N = 12$ $T_+ = 29$

$C_{.05} = 14$ (two tailed)

TABLE 6 OLD vs. RVV
Wilcoxon Test

In order to understand why a purview factor must be included as part of OMAC, consider the two paths shown in Figure 8. Path A includes nodes a, d, c, e, f, and Path B includes nodes a, b, c, e, and f. If own ship moves along segment a - d of Path A, it approaches the closest point of approach to the contact. Since the OMAC function (C_2), given above, includes a penalty for projected CPA's less than 2 miles, there is a non-zero penalty value produced by the second term of the equation. In comparison, segment b - c of Path B does not have a projected CPA violation. Therefore, the second term in the equation is zero along that segment. Transit time can be the same over segments a d c and a b c and therefore the penalty due to the time used (the value of the first term in the equation) is the same along both Path segments. As a result, Path B is always selected by the optimal synthesis process.

This result holds independent of the form of the equation and parameter values (A,B) provided there is a penalty for a projected CPA violation at some extended time.

But, subjects did not command that type of ship response. Instead, the ship is commanded along Path A toward point d until the subject decided that closer approach to the CPA was undesirable. When that point was reached, a maneuver to another course such as segment b-c was commanded. The purview limitation was included to represent that ship control characteristic.

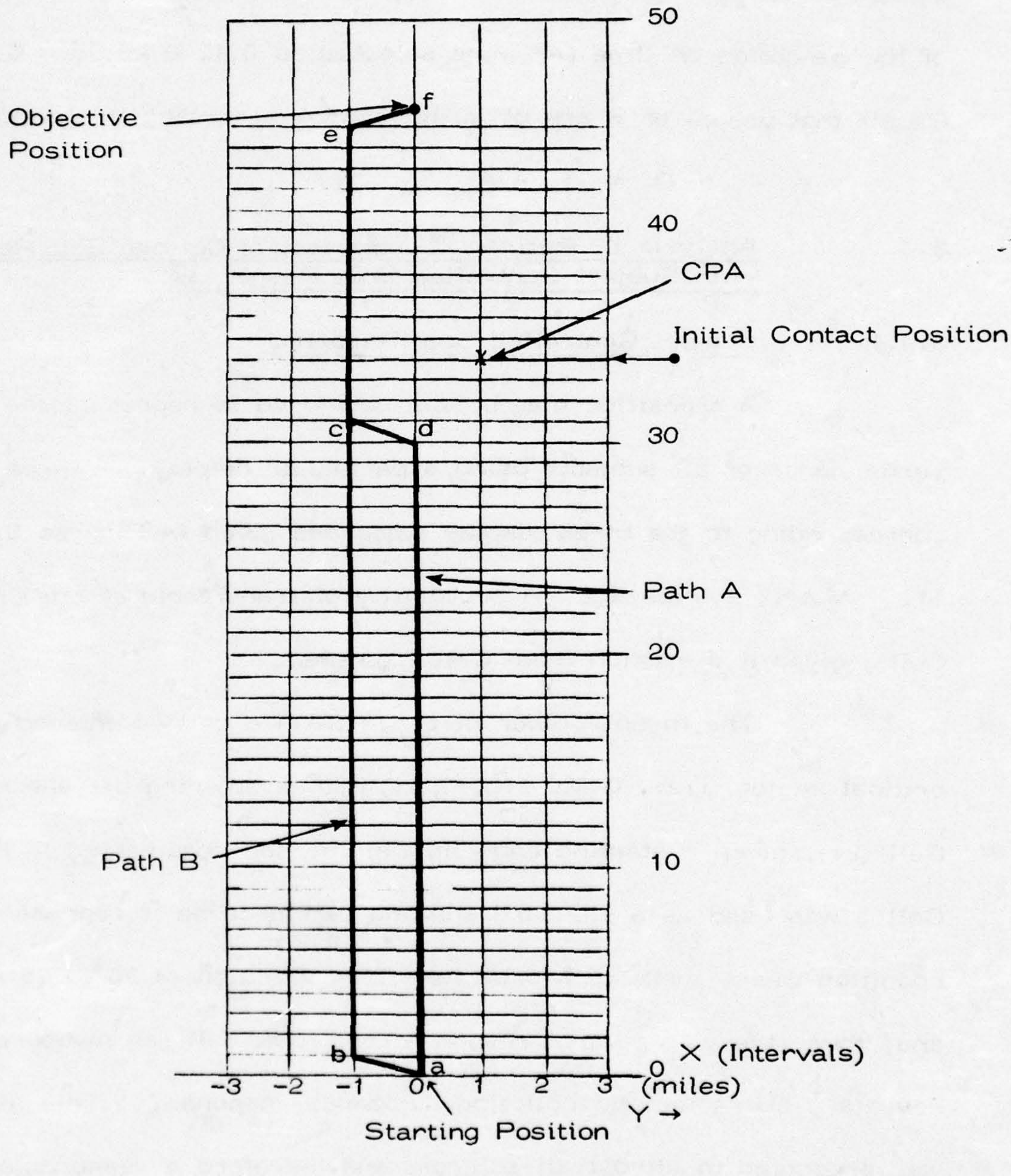

FIGURE 8 TWO POSSIBLE SOLUTION PATHS

Analysis of results with the one-contact problem established a set of parameter values for test in the 25-contact problem. Values of purview selected were 6.0, 8.3, 10, 12.5 miles. Values of the weighting on time (A) were selected as 0.1, 0.25, and 0.4. Recall that values of B are obtained from A according to the equation:

$$B = 1. - A$$

3.4 Analysis IV Results: Comparison of Optimal Ship Responses With Subject Controlled Ship Responses

3.4.1 Subject Controlled Ship Response

A transition matrix was developed to represent the composite performance of all subjects using a particular display. Three matrices corresponding to the three display types are given in Figures 9, 10 and 11. Matrix entries are the probability of transferring from Cell i to Cell j given a transition from Cell i occurs.

The mean number of times (MT) a cell is entered in the critical region (i.e., Cells 1-5, 7-11) before entering the absorbing Cell (21), given a starting entry in Cell 5, are documented in Figure 12. Cell 5 was used as a standard starting cell because it represents a condition where there is a projected CPA violation in 20 to 25 minutes, and, thus, the ship control response from that cell (as measured by MT) reveals a characteristic collision avoidance response. This situation was presented to almost all subjects and therefore a reasonable amount of data is available.

CELL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1		1.0																			
2	.25												.25	.50							
3		.25						.08	.08					.25	.33						
4			.43							.05						.10				.43	
5				.35						.02	.16	.02				.07	.12		.02	.23	
6					.47							.06						.09	.06	.31	
7													.20								.80
8	.25						.25							.50							
9								.17						.17	.50					.17	
10				.13	.25				.13						.13	.13				.25	
11				.07	.27					.20						.13	.13			.20	
12						.31					.15							.15	.08	.31	
13							.09													.03	.88
14								.02					.90							.08	
15									.09					.69						.23	
16				.03	.03				.03	.06	.03				.47		.06			.31	
17					.13						.06					.66				.16	
18											.06						.31			.63	
19						.15						.05						.03		.75	.03
20			.01		.01	.03		.00		.01	.01	.01	.02	.05	.03	.02	.01	.01	.22		.57
21							.03						.02						.02	.93	

FIGURE 9 CELL TRANSITION MATRIX FOR PACS DISPLAY

CELL

CELL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1							.50														.50
2	.20		.13				.13	.13						.33	.07						
3		.50						.04	.08	.04				.13	.17					.04	
4			.41			.03				.22						.08				.27	
5				.61						.07	.07					.02	.07			.17	
6					.57						.04	.07					.04		.18	.11	
7	.17												.17								.67
8		.14					.36							.50							
9			.23					.39							.15					.23	
10			.07	.17	.04				.38		.04				.07	.10				.14	
11				.06	.17					.56						.06	.06			.11	
12					.19						.31						.06	.06	.13	.25	
13	.02						.06													.04	.89
14		.03						.05					.82							.10	
15			.03					.03	.03					.59						.31	
16				.09						.15					.46					.30	
17					.03					.07	.13					.65		.03		.10	
18						.13						.06					.44			.38	
19					.01	.13						.08						.04		.74	
20		.00		.00	.01	.00		.01		.00	.01	.01	.01	.02	.02	.01	.01	.00	.21		.67
21													.05						.04	.91	

FIGURE 10 CELL TRANSITION MATRIX FOR OLD DISPLAY

CELL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1																					1.0
2	.43						.14	.29						.14							
3		.50						.07	.21						.07					.14	
4			.30		.03					.24	.06				.06	.09	.03			.15	.03
5			.02	.58						.07	.07						.09	.02		.16	
6					.53							.05					.03	.08	.11	.21	
7								.05					.21							.05	.68
8		.05					.55						.27	.10	.05						
9			.05				.05	.45							.35					.10	
10				.04				.04	.30		.04				.11	.19				.30	
11					.12					.36						.16	.12			.24	
12					.11	.06					.33							.22		.28	
13			.02				.08	.02	.02											.05	.83
14								.11					.70							.19	
15								.02	.10					.59						.29	
16				.09	.02				.05	.12	.02				.51		.02			.16	
17				.02						.02	.12					.51				.29	.02
18											.04	.21					.21		.13	.42	
19				.01		.21						.06						.05		.68	.01
20			.01	.01	.02	.02	.01	.01	.01		.00	.00	.03	.02	.02	.03	.02	.03	.18		.60
21		.01					.01				.01		.03						.04	.91	

FIGURE 11 CELL TRANSITION MATRIX FOR RVV DISPLAY

Cell	PACS	OLD	RVV
		Display Type	
1	.03	.07	.05
2	.08	.23	.13
3	.20	.40	.25
4	.45	.74	.68
5	1.17	1.07	1.10
7	.04	.14	.17
8	.03	.14	.21
9	.06	.17	.21
10	.11	.34	.33
11	.23	.11	.17

FIGURE 12 MEAN NUMBER OF TIMES A CELL IS ENTERED

3.4.2 Optimal Ship Response

Six sets of OMAC parameter values were used to determine optimal ship response patterns for the 25-contact problem. A tabulation of these parameter value sets is given in Figure 13. Results of the tests are the MT for each cell for each OMAC parameter set tested. Results are given in Figure 14.

3.4.3 Ship Response Comparison

Subject controlled ship response, as measured by the MT for each display type, was compared to the ship response for each OMAC. The sum of squared differences of MT on a cell-by-cell basis was used for the comparison. Results of the comparison for display type vs. OMAC purview are given in Figure 15. Results of the comparison of display type against the OMAC weighting on transit time are given in Figure 16. Best comparisons (least sum of squared differences) for the PACS, OLD, RVV displays are 12.5, 10, 12.5 miles purview respectively. Best comparison for time weighting is A = 0.1 for all display types. The percentage of sum of squares explained for PACS, OLD, RVV is 93.1, 88.8, and 84.3 respectively.

OMAC Number	Purview	Weighting A (Time)	Weighting B (CPA/TCPA)
1	12.5	.25	.75
2	10.5	.25	.75
3	8.33	.25	.75
4	6.0	.25	.75
5	6.0	.1	.9
6	6.0	.4	.6

FIGURE 13 OMAC PARAMETER VALUES

Critical Cell	OMAC					
	1	2	3	4	5	6
1	0.0	0.0	0.0	0.0	0.13	0.08
2	0.0	0.0	0.0	0.26	0.13	0.51
3	0.0	0.26	0.69	1.05	0.66	1.03
4	0.51	0.81	1.03	1.02	0.60	1.0
5	1.03	1.03	1.03	1.02	1.01	1.0
7	0.0	0.0	0.0	0.09	0.01	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.03	0.26	0.0	0.0
10	0.0	0.0	0.03	0.0	0.0	0.0
11	0.33	0.0	0.0	0.0	0.0	0.0

Entries are the mean number of times (MT) each cell is entered before the system enters the absorbing cell (Cell 21) given the cell sequence started in Cell 5.

FIGURE 14 MEAN NUMBER OF ENTRIES IN CRITICAL CELLS

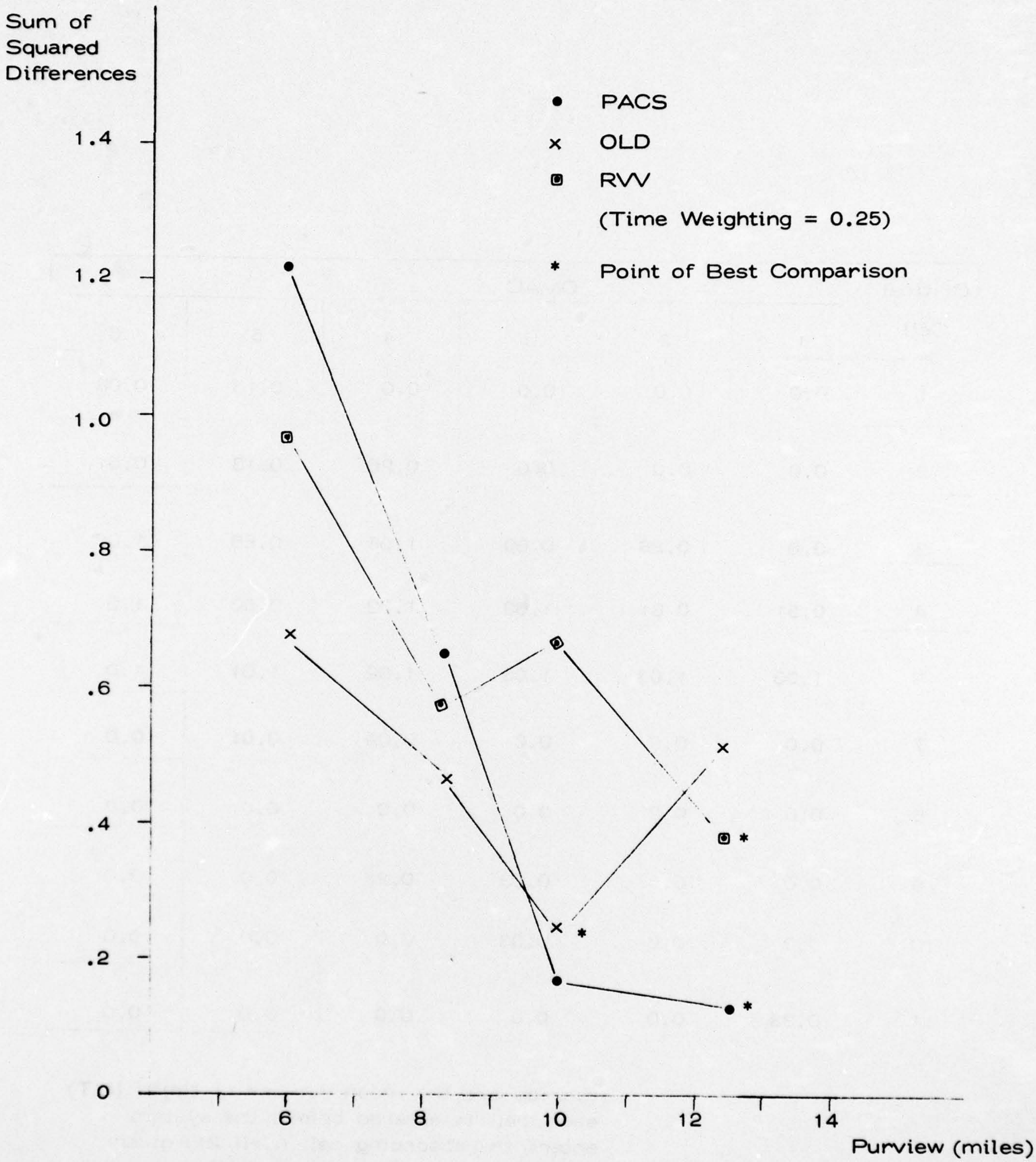

FIGURE 15 PURVIEW VS. DISPLAY TYPE

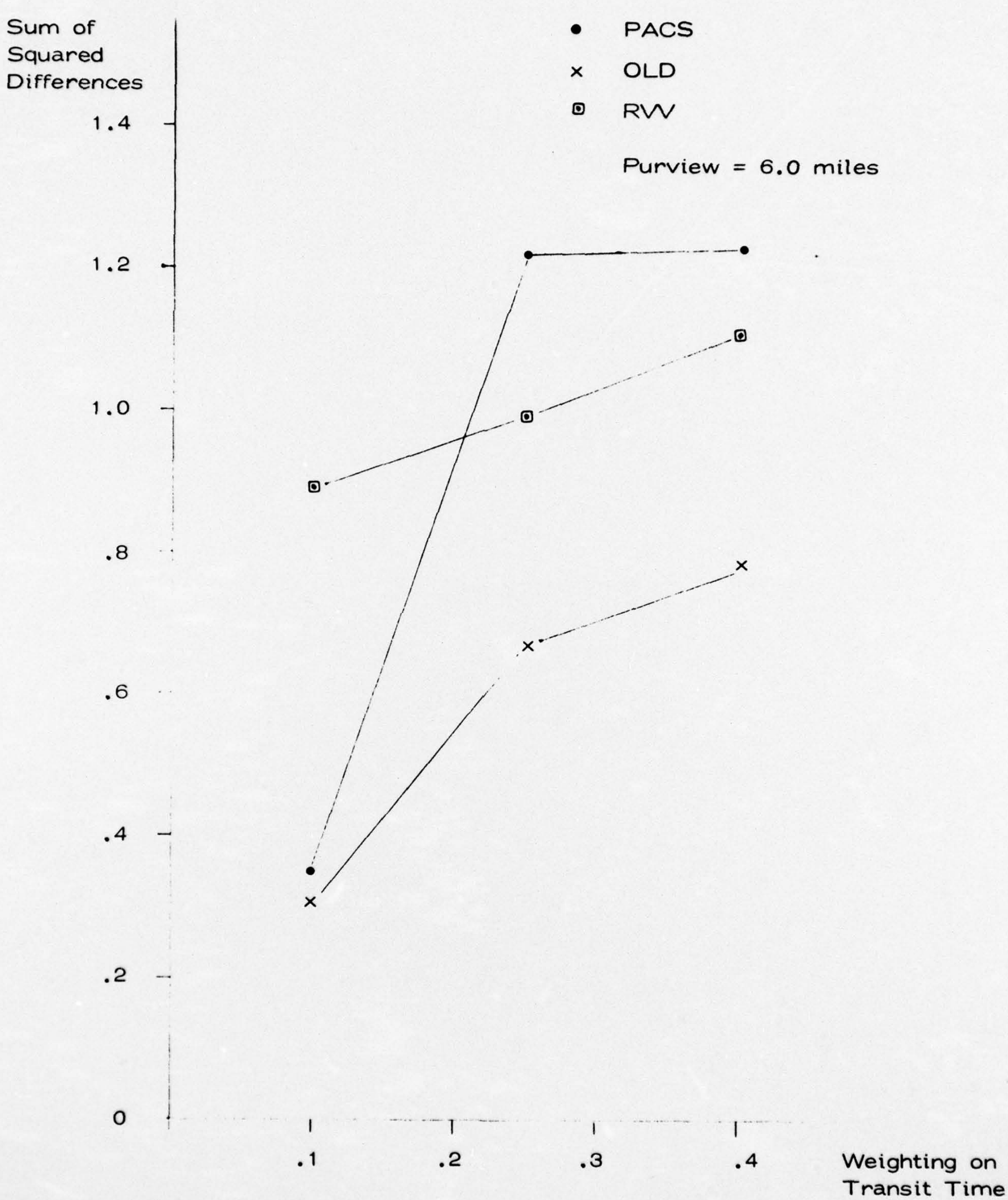

FIGURE 16 TIME WEIGHTING VS. DISPLAY TYPE

4.0 CONCLUSIONS

Analysis I shows that performance differences between certain display types are significant at the $\alpha = 0.10$ level. Summary measures which reveal this performance difference are time-to-CPA and distance travelled. The remaining summary measures do not show significant differences. Analysis II confirms that time-to-CPA is an important measure since with it significant differences in performance can be shown. Analysis II also reveals, via the measure MT (the mean number of entries in critical cells), the nature of the performance differences. From these results it is concluded not only that there are significant differences in performance with different displays, but also that performance measures which detect responses leading to a critical condition are more sensitive than summary measures of the critical conditions themselves.

Analysis III reveals that models of human operators controlling ships must include a purview factor. The purview factor used here was a radius within which a contact is considered. The model ignores contacts outside that radius. Note that other purview functions may be useful but some purview function was necessary to represent subject performance as a function of range to contact. The purview function is required to represent all performances, i.e., without regard to display type. It may also explain differences in performance with different displays; but, this property was not investigated.

Analysis IV reveals the effect of OMAC parameter values on the comparison of optimal control to the subject control data obtained in the experiment. Results show that performance is at least a function of transit time and CPA/TCPA weighting as well as purview. Results suggests that for the contact density of the experiment problem, PACS and RVV can be rated as at least 12.5 mile displays and that OLD is a 10 mile display. Results also suggest that a set of OMAC with multiple parameter changes - instead of one-at-a-time as was the case here - may improve modeling accuracy.

Consider now the primary purpose of the research as identified by the four questions presented in the introduction which concern methods of modeling the human operator. A method of computing the apparent OMAC from a set of candidate OMAC, has been demonstrated. The apparent OMAC has the parameter values of those analyzed that provide the best comparison to the experimental data. Also demonstrated is a method for using the OMAC to predict operator control actions in specific problem situations. The method uses an optimal control synthesis employing the representative OMAC as the criteria.

It is important to know whether or not a display configuration can affect the apparent OMAC. The results described here show that performance with different displays is significantly different

and also, the results support the hypothesis that the apparent OMAC changes with display design. While the statistical significance of the latter result has not been investigated because model validation is not complete, the results suggest that a display design affects the performance criteria used by the subject. A contrasting alternative is that the apparent OMAC is constant with variation in display design (for example, that OMAC is only a function of operator experience and problem instructions). With the alternative, differences in performance may exist with differences in display but the apparent OMAC is not different.

Many important questions have not been addressed by the work reported here. These include an investigation of more complex OMAC functions incorporating additional parameters, validation of the operators models (OMAC) and development of methods of analyzing the apparent OMAC to evaluate alternative designs.

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Naval Medical Research Institute
Bethesda, MD 20014

LCDR Thomas Berghage
Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, MD 20014

Dr. George Moeller
Head, Human Factors Engineering Branch
Submarine Medical Research Laboratory
Naval Submarine Base
Groton, CT 06340

CDR James Goodson
Chief, Aerospace Psychology Division
Naval Aerospace Medical Institute
Pensacola, FL 32512

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San Diego, CA 92152

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Crew Systems Department
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Johnsville
Warminster, PA 18974

CDR Robert Kennedy
Human Factors Engineering Branch
Code 5342
Pacific Missile Test Center
Point Mugu, CA 93042

Mr. Ronald A. Erickson
Head, Human Factors Branch, Code 4075
Naval Weapons Center
China Lake, CA 93555

Systems Engineering Test Directorate
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U. S. Naval Air Test Center
Patuxent River, MD 20670

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Annapolis, MD 21402

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Naval Coastal Systems Lab, Code 712
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Orlando, FL 32813

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Training Analysis & Evaluation Group
Naval Training Equipment Center
Code N-00T
Orlando, FL 32813

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Operations Research Department
Naval Postgraduate School
Monterey, CA 93940

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Washington, D. C. 20546

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Aberdeen, MD 21005

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Bolling Air Force Base
Washington, D. C. 20332

Chief, Human Engineering Division
Aerospace Medical Research Lab
Wright-Patterson AFB, OH 45433

Dr. Donald A. Topmiller
Chief, Systems Effect. Branch
Human Engineering Division
Wright Patterson AFB, OH 45433

Lt. Col. Joseph A. Birt
Human Engineering Division
Aerospace Medical Research Laboratory
Wright Patterson AFB, OH 45433

Dr. Stanley Deutsch
Office of Life Sciences
Headquarters, NASA
600 Independence Avenue
Washington, D. C. 20546

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Dr. Clyde Brictson
Dunlap and Associates, Inc.
115 South Oak Street
Inglewood, CA 90301

Dr. Alphonse Chapanis
The Johns Hopkins University
Department of Psychology
Charles & 34th Streets
Baltimore, MD 21218

Mr. J. G. Curtin
McDonnell Douglas Astronautics Company - East
St. Louis, MO 63166

Dr. Robert R. Mackie
Human Factors Research, Inc.
Santa Barbara Research Park
6780 Cortona Drive
Goleta, CA 93017

Mr. Alan J. Pesch
Eclectech Associates, Inc.
Post Office Box 179
North Stonington, CT 06359

Dr. Gordon H. Robinson
University of Wisconsin - Madison
Department of Industrial Engineering
1513 University Avenue
Madison, WI 53706

Mr. Lawrence Shumaker
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Dr. A. I. Siegel
Applied Psychological Services
404 East Lancaster Street
Wayne, PA 19087

Dr. W. S. Vaughan
Oceanautics, Inc.
3308 Dodge Park Road
Landover, MD 20785

Director, Human Factors Wing
Defense & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsville, Toronto, Ontario
Canada

Dr. A. D. Baddeley
Director, Applied Psychology Unit
Medical Research Council
15 Chaucer Road
Cambridge, CB2 2EF
England